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16. ABSTRACT The paper describes a comparison of the cost-effectiveness of four multicomponent, multimedia pollution abatement options: coal cleaning, limestone, limestone plus adipic acid, and coal cleaning plus limestone plus adipic acid. The comparison makes cost-effectiveness evaluations of the options applied to SO_2 and particulate discharges from coal combustion. This approach can be used to make similar comparisons for a variety of other pollutants that are components of complex process streams. It is not the intent to select one process over another, but rather to illustrate how the health benefits gained by each option may be gauged relative to incurred costs. This can determine, for example, whether money spent on removing 10% more of pollutant X from a process stream could be better spent on a process that removes 1% more of pollutant Y from the same source. To evaluate abatement systems, the effect of each system on pollutants of concern in the process stream must be compared. Comparisons can be made if emissions standards for chemical species (those for SO_2 and particulates, for example) are available. However, since standards have been established for only a few substances, surrogate goals -- derived from a methodology that translates toxicological data into acceptable levels for pollutants in discharge streams -- are used. Multimedia Environmental Goals (MEG) methodology is an integral part of the EPA/IERL-RTP program and is used to guide the development of abatement technology more effectively.

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EPA scientists are developing methods to compare the cost-effectiveness of multicomponent, multimedia

Pollution abatement options

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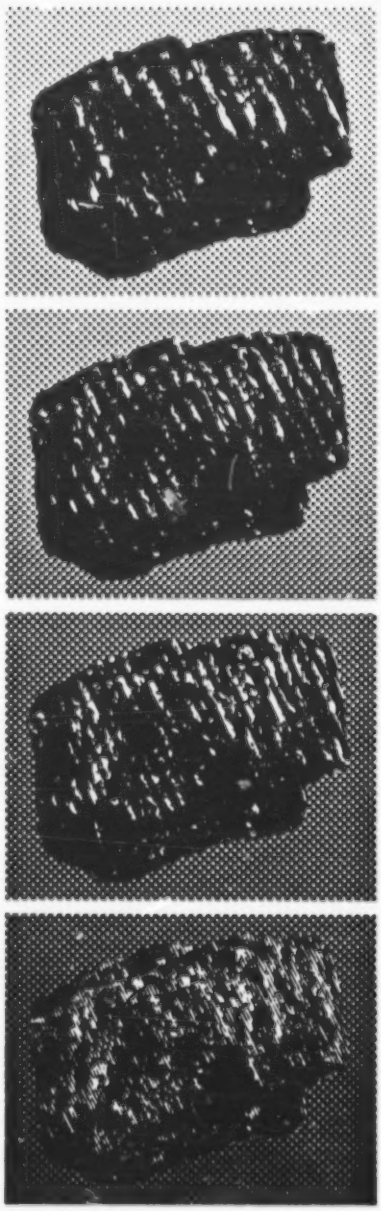
Emerging alternative fuel technologies based on coal, as well as conventional coal combustion technology, have the potential to cause serious health and environmental damage if pollutant discharges go unchecked. Pollutants of concern range from simple gases, such as carbon monoxide (CO) and sulfur dioxide (SO_2), to more complex substances, such as polynuclear aromatic hydrocarbons and nitrogen- and sulfur-containing heterocyclics.

For a number of years, the U.S. EPA Industrial Environmental Research Laboratory (IERL) has been developing and evaluating a variety of pollution abatement systems for coal-based technologies. These systems have varying degrees of effectiveness, as well as associated costs for eliminating or minimizing environmental and health damage.

Although various abatement processes are available, or can be designed, no single measure or combination of measures can reduce releases of all pollutants to such a degree that there will be minimal risk without prohibitive expenses. Thus, it becomes necessary to choose or develop those abatement processes that, for reasonable costs, provide a level of health/environmental protection compatible with established criteria, and with realistic future goals, while at the same time ensuring that energy needs are met.

The following example of the IERL approach to making cost-effectiveness evaluations of four different control options applies to SO_2 and particulate discharges from coal combustion. This approach, however, can be used to make similar comparisons for a variety of other pollutants that are components of complex process streams. It is not the intent to select one process over another, but rather to illustrate how one can gauge the health benefits gained by each option relative to incurred costs. This way one may judge, for example, whether money spent on removing 10% more of pollutant X from a process stream could be better spent on a process that removes 1% more of pollutant Y from the same source.



To evaluate abatement systems, one must compare the effect of each system on pollutants of concern in the process stream. Comparisons can be made if emissions standards for chemical species (those for SO_2 and particulates, for example) are available. However, since standards have been established for only a few substances, surrogate "goals"—derived from a methodology that translates toxicological data into "acceptable levels" for pollutants in discharge streams—are used. "Multimedia Environmental Goals (MEG) Methodology" (*1-4*) is an integral part of the IERL program and is used to guide the development of abatement technology more effectively.

The MEG methodology

Multimedia environmental goals (MEGs), developed in 1976, are *estimated* levels of contaminants or degradants in ambient air, water, or land, or in discharges to ambient/environmental media, that will not produce adverse effects in receptor populations. Ambient goals (AMEGs) are applied to continuous exposure. Discharge MEGs (DMEGs) are based on eight-

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hour exposure times. The MEG data base contains over 1000 chemical species and their assigned target concentrations. These MEG values were not intended to be used as *de facto* regulations or guidelines, but rather to rank contaminants according to the relative severity of their health or ecological effects.

Contaminants of process streams can be ranked and compared on health bases according to the following expression:

$$DS = \frac{\text{Measured concentration of stream component}}{\text{DMEG for compound}}$$

where DS is the discharge severity. A DS value greater than one leads to the presumption that the measured concentration is potentially harmful.

The discharge severity, however, gives no indication of the amount of material being emitted to the environment. Obviously, if two systems have the same discharge severity, but the flow rate of the first has one thousand times the flow rate of the second, the first poses a much greater potential danger. To compare pollutants, then, the DS values for each pollutant are multiplied by the stream mass flow rate. This results in a weighted discharge severity (WDS) of each.

MEG limitations

Limitations and reservations of the MEG methodology were discussed by a panel of nongovernmental scientists during a review of IERL's Environmental Assessment Program in January 1979 (*6*). In response to the panel's recommendations and concerns of others regarding the methodology, IERL has undertaken to improve the methodology, with a focus on the following areas:

Carcinogens and teratogens are evaluated according to a method distinct from compounds judged to be noncarcinogens.

Significantly less reliance will be placed on TLV and LD_{50} values. For substances assigned MEG values based on such information, a comprehensive evaluation program has been instituted by EPA's Environmental Criteria and Assessment Office to obtain health effects information.

Compounds for which toxicological data are inadequate will be addressed by *reference* compounds for which there are adequate data.

Uncertainties will be more fully described, and safety factors will account for such concerns as persistence, environmental transport, and bioaccumulation.

When the WDS values of each stream component are added together, the result is the total weighted discharge severity (TWDS) of the stream. Units are generally expressed in kilograms per hour. TWDS is the best single value for evaluating the potential harm that a discharge stream may cause.

The usefulness of the TWDS in making comparisons between abatement technologies depends upon the validity of the DMEG. Because the derivation of these assigned values has a number of limitations, this derivation will be examined before an example of the application of the methodology is given.

Derivation of DMEGs

Relatively few substances addressed by federal standards or guidelines are pertinent to ambient air exposure. A much larger grouping of chemicals is addressed by occupational standards, such as OSHA standards, the threshold limit values (TLVs) of the American Council of Governmental and Industrial Hygienists (*5*), LD_{50} values, and recommended criterion levels of the National Institute for Occupational Safety and Health (NIOSH). When no federal standards for ambient media exist, constant fractions of those pertinent occupational data are used as DMEGs.

Limitations of time and resources have not permitted a comprehensive evaluation of the health effects associated with many compounds. Reliance has therefore been placed on commonly available reference sources, such as the NIOSH Registry of Toxic Effects of Chemical Substances. It is recognized that such reference sources often contain information of limited applicability to MEG development, and often do not reflect advances in knowledge or contain the quality of information that would be developed by a comprehensive health assessment.

In addition, the arbitrary use of safety factors without supporting rationale presumes that such factors may be overly conservative in some instances and not sufficiently stringent in others. The factors currently employed in the MEG methodology were chosen to ensure an ample margin of safety. At present, they do not account for such concerns as persistence, bioaccumulation, synergism, and antagonism.

It is also recognized that uncertainties associated with the derivation of MEGs are not sufficiently accounted for in the methodology. For example, MEG values are expressed as a concentration without confidence limits.

Criticisms of TLVs

Many have questioned the use of TLVs for developing MEG parameters. Specific criticisms of TLV use are:

TLVs are comparable only when metabolic pathways of substances are similar.

TLVs often are based upon different biological end points. Thus, comparisons are valid only when the end points are the same.

TLVs reflect long-term intermittent exposure, whereas DMEG values address only eight-hour exposures.

Threshold concentrations are inappropriate for evaluating non-threshold pollutants, notably carcinogens.

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A power plant study

The usual way to perform a cost comparison of pollutant abatement systems is to compare how much it costs to remove 1 kg/h of a pollutant from a stream for a given plant production rate. This approach fails to take into account other pollutants in the stream that may also be affected, dependency of the net improvement on the chemical form of the removed pollutant, and the media into which the pollutant is discharged.

The method presented herein does not have these deficiencies. To illustrate, four different flue-gas desulfurization (FGD) possibilities will be compared: physical coal cleaning, a limestone-scrubbing FGD process, a limestone-scrubbing FGD process with adipic acid added, and a combination of all three processes.

This example involves a currently operating 500-MW power plant. The coal contains 3.5% sulfur and 17.9% ash (dry basis). (The same coal was used in a Tennessee Valley Authority study (*7*, *8*) on comparative costs.) The bottom ash from the boiler contains 20% of the ash and 5% of the sulfur entering the boiler. The plant has multicyclones that remove 70% of the ash left. The remaining 95% of the sulfur is assumed to be emitted into the atmosphere as SO_2.

The coal-cleaning data are based on a paper by Kilgroe (*9*). Coal cleaning is assumed to reduce the sulfur to 2% and the ash to 8% of the resultant washed coal (dry basis). Of the initial heat value, 94% is recovered. Since the boiler must produce the same power output, 6.4% more coal must be used than when raw coal is charged to the boiler.

The limestone FGD process is assumed to remove 80% of the sulfur entering the unit. This process, according to Torstrick et al., requires 1.3 moles of calcium carbonate ($CaCO_3$) per mole of sulfur removed (*8*). The scrubbing action, plus the multicyclones, removes 99% of the fly ash entering.

When 1500 ppm of adipic acid is added to the limestone slurry, the FGD system is assumed to remove 90% of the sulfur entering with more efficient utilization of limestone: 1.15 moles of $CaCO_3$ per mole of sulfur removed (*4*). No increase in particulate removal is assumed over the straight limestone FGD process.

When the coal cleaning process is used in combination with the limestone/adipic acid FGD, it is still assumed that 5% of the sulfur entering the boiler leaves with the bottom ash, and 90% of the sulfur entering the boiler is removed in the FGD unit. Similarly, 99% of the ash entering the boiler is removed in the multicyclones and scrubbers. A summary of these processes is given in Table 1.

Obtaining cost figures

The cost figures, obtained by Dr. Vincent W. Uhl of the University of Virginia, are based on data from References *9–11*. They are expressed in terms of kilowatt-hours of electricity produced.

The usual approach for comparing desulfurization processes would be to determine the cost required to reduce the SO_2 released to atmosphere by 1 kg/kWh of electricity produced. This approach implies that the cost of reducing the output flow rate of SO_2 by 0.0005 kg/kWh is independent of the concentration of SO_2 present. That is not true, as can be seen from Table 2.

If the concentration of SO_2 is to be between 0.023 and 0.0115 kg/kWh, coal cleaning alone can be used. However, if it is to be reduced between 0.0023 and 0.00115 kg/kWh, not only is coal cleaning required but also another, more expensive process must be added (for example, limestone FGD).

A better method for comparing processes involves determining the minimum incremental cost of removing the next 1 kg/kWh. This method charges all the additional cost to the additional amount of SO_2 removed. In the last column of Table 2, it is shown that reducing the original amount of SO_2 released from 0.023 to 0.0115 kg/kWh will cost \$0.22 per kg of SO_2 removed, while reducing it from 0.0023 to 0.00115 kg/kWh will cost \$1.22 per kg of SO_2 removed. This is almost 5.6 times as much per unit removed as for the removal of the first 50% of the SO_2.

TABLE 1
Removal efficiencies

Boiler	
20% of ash entering unit	
5% of sulfur entering unit	
Multicyclones	
70% of ash entering unit	
0% of sulfur entering unit	
Coal cleaning	
53% of sulfur entering unit	
63% of ash entering unit	
6.0% of coal entering unit	
Limestone flue-gas desulfurization (scrubber) plus multicyclones	
80% of sulfur entering unit	
99% of ash entering unit	
Limestone flue-gas desulfurization plus adipic acid addition and multicyclones	
90% of sulfur entering unit	
99% of ash entering unit	

SO_2 particulate equivalents

As noted before, the above analysis looks at only one pollutant, SO_2. Table 3 compares the costs when only the amount of particulate matter removed is considered. It shows that adding adipic acid does nothing to assist particle removal, whereas Table 2 shows that this addition is a very cost-effective means of assisting SO_2 removal. However, neither Table 2 nor Table 3 identifies the most cost-effective scheme for removing both SO_2 and particulate matter.

Combining the benefits of SO_2 control with those of particulate matter removal necessitates a common denominator—1 kg of particulate matter removed must be equivalent to the removal of x kg of SO_2. The approach can be based on EPA emission standards for new facilities (*12*). The particulate standard is 0.054 kg/10^6 kcal of energy in coal. The proposed 1983 standards for coal containing 3.5% sulfur state that no more than 10% of the sulfur may leave in the flue gas. It is assumed that the coal has a heating value of 5833 cal/g; therefore, less than 353.4 μg of particulate matter and less than 7000 μg of SO_2 can be emitted per gram of coal charged. This means that 1 g of particulate matter is equivalent to 19.8 g of SO_2.

These results can also be expressed in terms of the amount of pollutant emitted per cubic meter of flue gas. The flow rate of the flue gas is 1.83 million m^3/h (at 21 °C and 1 atm pressure). On this basis, the standard is 33 600 μg of particulate matter/m^3 of flue gas, and 665 000 μg of SO_2/m^3 of flue gas.

Whenever coal cleaning is used, 6.4% more coal is required in order to make up for the loss of coal incurred in this process. Because of the way the 1983 proposed standard is written, this means that more SO_2 can be emitted per cubic meter. When coal cleaning is used, the SO_2 standard is 706 900 $\mu g/m^3$. The standard is made dimensionless by dividing by the density of the gas and 10^6 μg/g. This division results in a standard for particulate matter of 2.786×10^{-5} g/g, and for SO_2 of 5.52×10^{-4} g/g (5.86×10^{-4} g/g when coal is cleaned).

Dividing the flow rate of the pollutant discharged by the proposed standard places the pollutants on the same basis. A single value is obtained when the results are added: Each pollutant present has been converted into the equivalent number of kilograms per hour of a fictional pollutant whose maximum standard emission rate is 1 g/g of flue gas emitted. This fictional pollutant, if pure, would just meet pollution standards.

Table 4 presents the costs for removing this fictitious pollutant. When particulate and SO_2 removal are considered together, the addition of adipic acid to the limestone process is not as cost-effective as when only SO_2 removal is considered; this is because no additional particulate matter is removed, and the removal of 1 kg/h of particulate matter is equivalent to removing approximately 20 kg/h of SO_2. Thus, for a combination of the effects of the two pollutants, the more important one to remove, in terms of kilograms per hour, is particulate matter.

The above procedure might be adequate if all of the potentially hazardous pollutants had emission standard maximum concentrations. This, however, is not the case. Many compounds for which there are no standards, such as mutagens and carcinogens, potentially are more dangerous than either particulate matter or SO_2. In addition, the new-source performance standards are based on the best available control technology.

For comparative purposes it would be better if the weighting factors were related to the potential damage that each pollutant would cause. This can be done through use of the assigned health-based DMEG values.

A substitute for standards

Discharge MEGs are calculated by the use of unsophisticated mathematical models. The current methodology

uses 14 different models. Approximately 650 chemical species have been assigned DMEG values. Values are expressed in $\mu g/m^3$ (gases), $\mu g/L$ (liquids), and $\mu g/g$ (solids). As shown below, the DMEG concept is applied to analysis of the control options previously discussed.

The use of DMEGs permits not only a similar, more extensive multicomponent comparison than that based on emission standards, but it also permits a multimedia comparison of waste streams leaving different processes. For any stream, the total weighted discharge severity is defined as:

$$\mathrm{TWDS_s} = \sum_i M_i/\mathrm{DMEG}_i/\rho_i = \sum_i \frac{dc_i \times M}{\mathrm{DMEG}}$$

where M_i is the mass flow rate of component i in the exiting stream, kg/h; M is the mass flow rate of the exiting stream, kg/h; dc_i is the discharge concentration of component i, $\mu g/m^3$, $\mu g/L$, $\mu g/g$; DMEG_i is the discharge multimedia environmental goal for component i, $\mu g/m^3$, $\mu g/L$, $\mu g/g$; ρ_i is the density of the component i at 25 °C and 1 atm for gases and liquids, $\mu g/m^3$ or $\mu g/L$ (ρ_i equals 1.0 for solids).

For any plant or process, the total weighted discharge severity ($\mathrm{TWDS_p}$) is defined as the sum of $\mathrm{TWDS_s}$'s for all the exiting streams from a plant or process:

$$\mathrm{TWDS_p} = \sum_s \mathrm{TWDS_s}$$

The method can be illustrated by again using SO_2 and particulate matter. The health DMEG for SO_2 is 13 000 $\mu g/m^3$ (*11*), that for particulates in flue gas, based on individual components of the particulates, is 877 $\mu g/m^3$ (*13*). The health DMEG for solids is 3420 $\mu g/g$ of solids discharged.

Table 4 gives the cost comparisons for their abatement. These results are essentially in the same ratio to each other as those for the emission standards given in Table 4. They differ in magnitude because DMEGs are an average of 2.2% of the value of the equivalent emission standard, because solid streams are considered pollutant streams when DMEGs are used, and because the ratio of the SO_2 DMEG to the DMEG of particulate matter is 14.8, while the equivalent ratio for the emission standard is 19.8. So, for a gaseous effluent, 1 g of particulate matter has the same potential for doing harm as 14.8 g of SO_2.

To take into account synergisms and antagonisms between any two compounds in a mixture, the TWDS formulas could be modified by the addition of a term:

$$\mathrm{TWDS_s} = \sum_i (M_i/\mathrm{DMEG}_i/\rho_i + \sum_j kM_{ij}/(2\ \mathrm{DMEG}_{ij}/\rho_{ij})$$

where M_{ij} is the lower of mass flow rates for component i or j; DMEG_{ij} is the DMEG for the synergistic or antagonistic effect between i and j; k is a constant that equals zero if there is no synergism or antagonism, 1 if there is a synergistic effect, and −1 if there is an antagonism; ρ_{ij} is the density for the component i or j, which has the lowest mass flow rate.

The initial scope of the MEG program did not consider synergisms or antagonisms. DMEG values for these

TABLE 2
Sulfur dioxide pollution abatement costs

Process	Amount of pollution, kg/kWh × 10^3	Pollution abatement cost, $/kWh	Cost/pollution abatement improvement [a], $/kg	% improvement [a], ΔSO_2/kWh × 10^2 / SO_2/kWh	Incremental cost per pollution abatement improvement [b], $\Delta$$/kWh / kg SO_2/kWh, $/kg
No control	23	—	—	—	—
Coal cleaning	11.5	0.0025	0.217	50	0.22
Limestone	4.6	0.0046	0.250	80	0.31
Limestone + adipic acid	2.3	0.0047	0.227	90	0.04
Coal cleaning + limestone + adipic acid	1.15	0.0061	0.279	95	1.22

[a] Basis: no control.
[b] Basis: previous process in table.

TABLE 3
Particulate matter pollution abatement costs

Process	Amount of pollution, kg/kWh × 10^3	Pollution abatement cost, $/kWh	Cost/pollution abatement improvement [a], $/kg	% improvement [b], ΔParticulate/kWh × 10^2 / Particulate/kWh	Incremental cost per pollution abatement improvement [b], $\Delta$$/kWh / Δkg Particulate/kWh, $/kg
No control	15	—	—	—	—
Coal cleaning	5.9	0.0025	0.272	61.5	0.27
Limestone	0.49	0.0046	0.317	96.7	0.49
Limestone + adipic acid	0.49	0.0047	0.324	96.7	—
Coal cleaning + limestone + adipic acid	0.19	0.0061	0.412	98.7	4.67

[a] Basis: no control.
[b] Basis: previous process in table.

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TABLE 4

Pollution abatement costs for four desulfurization processes, based on emission standards

Process	Amount of pollution $TWDS_C$/kW kg/kWh	Pollution abatement cost $/kWh	Cost/pollution abatement improvement [a] $\frac{\$/kW}{\Delta TWDS_{PAD}/kW}$ $/kg × 10^6	% improvement [a] $\frac{\Delta TWDS_{PAD}/kW}{TWDS_{WC}/kW}$ × 10^2	Incremental cost per pollution abatement improvement [b] $\frac{\Delta\$/kW}{\Delta TWDS_{WD}/kW}$ $/kg × 10^6
No control	580	—	—	—	—
Coal cleaning	230	0.0025	7.1	60.3	7
Limestone	26	0.0046	8.3	95.5	10
Limestone + adipic acid	22	0.0047	8.4	96.2	25
Coal cleaning + limestone + adipic acid	10	0.0061	10.7	98.2	117

. . . based on health DMEGs

Process	Amount of pollution $TWDS_C$/kW kg/kWh	Pollution abatement cost $/kWh	Cost/pollution abatement improvement [a] $\frac{\$/kW}{\Delta TWDS_{PAD}/kW}$ $/kg × 10^6	% improvement [a] $\frac{\Delta TWDS_{PAD}/kW}{TWDS_{WC}/kW}$ × 10^2	Incremental cost per pollution abatement improvement [b] $\frac{\Delta\$/kW}{\Delta TWDS_{WD}/kW}$ $/kg × 10^6
No control	23 000	—	—	—	—
Coal cleaning	9 300	0.0025	0.182	60	0.18
Limestone	1 130	0.0046	0.210	95.1	0.26
Limestone + adipic acid	900	0.0047	0.213	96.1	0.43
Coal cleaning + limestone + adipic acid	400	0.0061	0.270	98.3	2.8

[a] Basis: no control.
[b] Basis: previous process in table.
$TWDS_{WD}/kW$ = best estimate of $TWDS_C/kW$ for process listed previously in the table.
$TWDS_C/kW$ = best estimate of TWDS/kW for process with control device(s).
$TWDS_{WC}/kW$ = best estimate of TWDS/kW for process without control device(s).
$\Delta TWDS_{PAD}/kW = TWDS_{WC}/kW - TWDS_C/kW$ = pollution abatement decrease.
$\Delta TWDS_{WD}/kW = TWDS_{WD}/kW - TWDS_C/kW$ = incremental pollution abatement decrease.

types of effects have therefore not been determined.

A simple approach

The advantage of using DMEGs in cost comparisons of pollution abatement processes is that multicomponent, multimedia comparisons may be made. But, as stated, DMEGs for all compounds have not as yet been developed. In addition, there is controversy over some values that are given.

The advantage of the emission standards approach is that current or proposed standards are used; but since standards have been set for only a few substances, the approach is limited. The disadvantage of using a single-pollutant/single-media method is that it is too confining. A process may remove one pollutant but neglect more hazardous ones, or it may remove a pollutant from the air and put it into water, where it may be more dangerous. A single-pollutant/single-media cost comparison would be specious.

The DMEG approach is simple. All the models mentioned assume that there is a linear relationship between potential damage and the amount of the pollutant emitted. When the four different incremental cost comparisons are examined, the results are in the same order, with the exception of the adipic acid addition to limestone scrubbing (no coal cleaning). This exception, as already noted, is based mainly on the assumption that no additional particulate matter is removed.

As knowledge of the potential harm that may result from discharging of various compounds to different media increases, cost comparisons based on the single-media method become more and more unacceptable. Multifactor methodologies, such as the one presented here, can lead to cost-effective pollution abatement strategies and can better address the complex health and environmental concerns posed by fossil-fuel-based technologies.

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William D. Baasel (*above*) *is professor of chemical engineering at Ohio University. He was on loan to the U.S. Environmental Protection Agency between June 1978 and September 1980. He currently has a cooperative agreement with EPA to evaluate the cost of acid rain mitigation. He is also involved in using radiation to reduce polycyclic organic matter emissions. He is the author of a book, "Preliminary Chemical Engineering Plant Design," and is chairman-elect of the Chemical Engineering Division of the American Society for Engineering Education.*

Mark M. Greenberg *received a B.S. in biological sciences at Drexel University in 1962 and an M.S. in biochemistry at Purdue University in 1965. He currently is an environmental scientist in EPA's Environmental Criteria and Assessment Office.*

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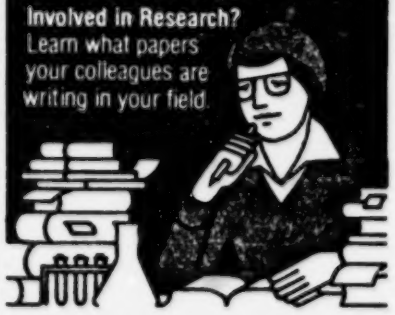

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